Connections

The Structural Details of an Art Gallery

by Amy M. Kim
B.S.A.D. Massachusetts Institute of Technology, June 1991

Submitted to the Department of Architecture in partial fulfillment of the requirements for the degree of Master of Architecture at the Massachusetts Institute of Technology, September 1995.

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Accepted by — Ellen Dunham-Jones, Assistant Professor of Architecture, Chairman, Departmental Committee on Graduate Students

To my parents, for all their love, support, and prayers.

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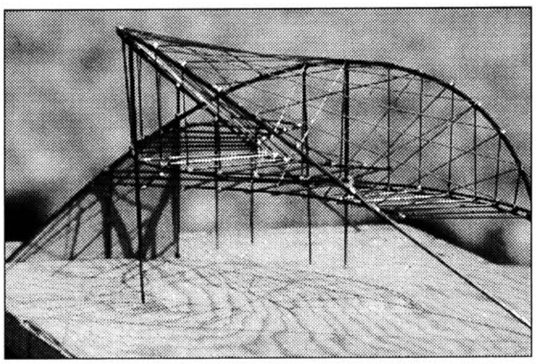
Connections describes the physical means by which the building transforms concept into reality. These connections link user and building; site and building; program and building; art and public. This study uses as a starting point a previous design project where advanced technology allowed and informed the complex geometry and overall composition of the building. This thesis investigates the assemblage of the major building components to demonstrate how the connections make the building. This model will show how these technologies best realize the intent of the program. This art gallery gives up-and-coming local and regional artists and designers the opportunity to exhibit their work. The combination of the building and program will increase the interaction between the general public and art. The building design distinguishes itself from the typical temple- or vault-like quality of the art museum and exhibits a more inviting form. These connections not only make the building; they connect art and public in a more dynamic relationship.



3.1 Conceptual Model.

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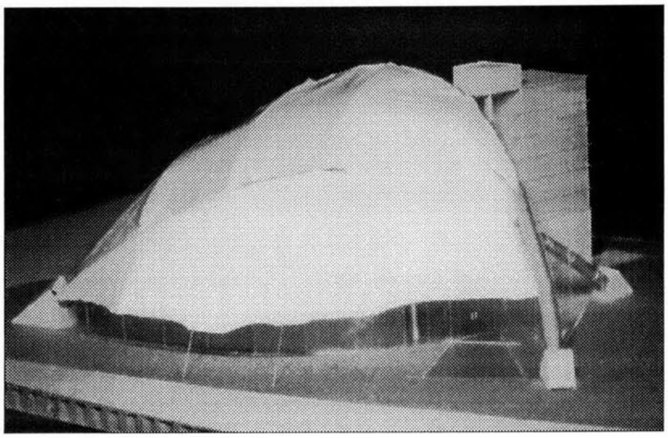
Introduction

Connections, the means by which elements are integrated and incorporated into one another, are the primary concerns of this structure, both physically and theoretically. Physically, the connections are the stitching that bring the major components of the building together. They perform the same function as the seams of a piece of clothing. The stitching is what makes a suit, shirt or slacks. It keeps the pattern pieces together. This analogy extends to the physical details of the building: they are what keep the building together and what give the structure its character. They are an expression of the general concept of the building. Theoretically, the gallery provides a locus through which society, first at a community level, then at a larger socio-cultural level, may interact. As an architectural work, the building's structure is an expression of the various technologies used to assist in its design development.



5.1 Model of the art gallery.

The gallery belongs to the Cambridge community. Although its appearance distinguishes itself from the typical Cambridge brick and stone, the gallery is very much a part of the community. The building establishes a connection with the public. A gallery is a house for artistic works, paintings, sculpture, design. Works from all parts of the Northeastern region converge in this one place. The public is invited to come in, to interact. The connection between the public and art is made. The glass "display box" sits between Massachusetts Avenue and Main Street displaying its wares. Is art down to a lower level? Actually, the gallery elevates art to a level where everyone can participate. The art world no longer selects its client; the public chooses whether to interact or completely ignore it.

From the outside the individual is introduced to the beauty of the building through the crafted details, all of which interrelate and create dynamic connections with each other. The individual may or may not be conscience of the details, the art of the building, but he or she will be affected nevertheless. The exposed details inform the person of the building's "story". Each detail tells its own anecdote, and all are interdependent on the other. The individual connection is a microcosm of the whole assemblage. The building, as an extension of the architect, has established a connection with the individual.

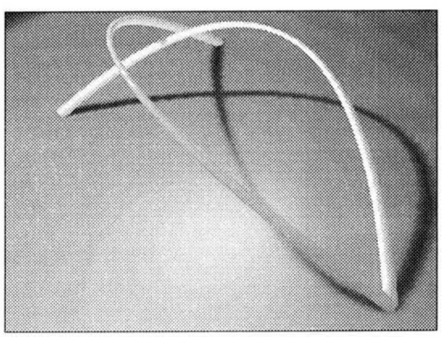
Once the individual enters the building, he or she becomes part of the display. The platforms in the gallery serve as display areas for the art work, and these platforms in turn become a crafted piece on display. People interact with the actual pieces of art. Perceptions change. Viewed from outside, the building serves as a frame for the activities within. From the inside, the building frames the city's activity, and essentially the city becomes gallery.

Components

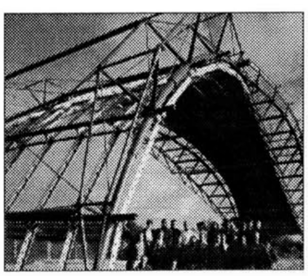
Industrialization of the process of construction is a question of new materials...our technologists must and will succeed in inventing materials that can be industrially manufactured and processed and that will be weatherproof, soundproof and insulating. I am convinced that traditional methods of building will disappear.

– Mies van der Rohe 1924 in G (Gestaltang) magazine.

Arches



7.1 Computer-generated model of arches.

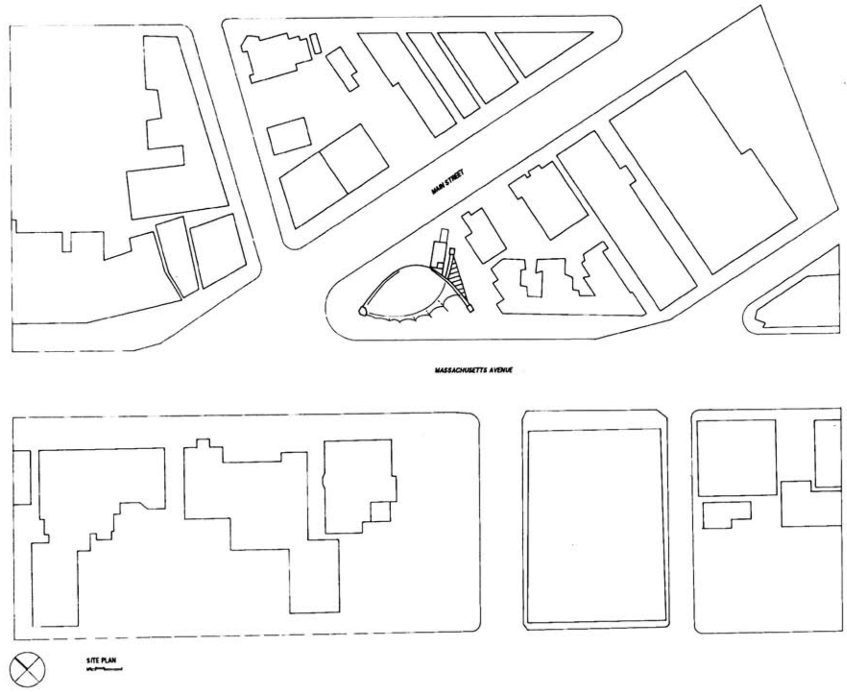


7.2 Bay of the roof of the Channel Tunnel Railway Terminal Building, Nicholas Grimshaw.

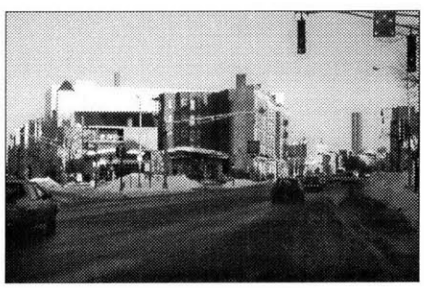
The two primary structural elements are made of telescoping circular sections like that of the Channel Tunnel Railway Terminal in Waterloo by Nicholas Grimshaw (Fig. 7.2). The telescoping sections are lighter and more economical than solid steel. The hollow sections enable the arches to have a dual function. Not only are they structural, but they are also part of the mechanical system used to circulate air in the gallery. The arches are sandwiched between two layers of glass, creating a plenum. The vents in the arches would draw the air out of the plenum and expel it into the exterior environment.

The arches, angled at 45°, begin at a point, extend away from each other and pass by as shown in Fig. 7.1. The configuration of the arches is derived from information provided from the site. The span of the taller arch is parallel with Massachusetts Avenue, and the span of the shorter arch is parallel with Main Street. This orientation gives more attention to Massachusetts Avenue where more activity occurs. The secondary structural system, i.e. the joints to support the roof and the glazing, branch

8.1 Site plan.



off the arches. The arches delineate the physical and imaginary lines of the building.



8.2 View of site from Massachusetts Avenue.

The configuration of the arches responds directly to the triangular shape of the site making the building site-specific (Fig. 8.1). In terms of context, it is a new vocabulary amongst the Cambridge brick and concrete warehouses in the surrounding areas, but the building is located just down the street from M.I.T., a university known for its technological and scientific discoveries and inventions. It is fitting, then, to have this display of technology mark this node of the city that serves as a transition point between Central Square & the M.I.T. campus.

The two principal methods of making structural hollow sections are the seamless method or by welding. Welded hollow sections are produced by a range of processes including butt or continuous weld, electric weld, spiral weld and submerged arc welding. The gallery arches require the use of both the electric weld process as well as the submerged arc welded process. The majority of hollow tube construction are produced by the electric weld method, which can produce circular sections from 2 in. diameter up to 20 in. diameter.[1]

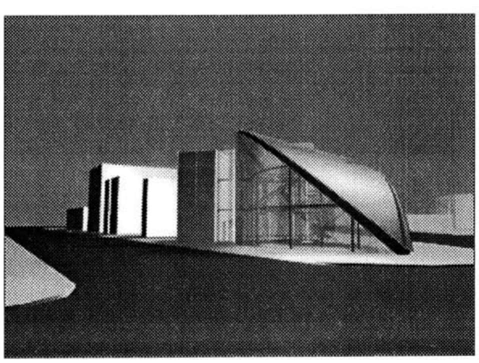
Electric weld tubes can be produced as hot finished or cold-formed sections. Both processes use hot finished strip as their "feed stock" and are initially formed into cold round sections and welded. Cold-formed sections can be finished into circular shaped cold, while hot finished sections can be heated and formed into the circular shape within the normalizing temperature range.[2]

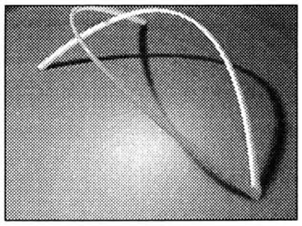
Since the largest diameter of the arch section is 3 feet, the submerged arc welded process is needed. This process is generally used for tubes from over 20 in. diameter up to 84 in. diameter. Larger sizes are formed from 2 semi-circular tubes while the smaller sizes are are formed from single circular rolled plate with the final weld being made by the submerged arc (SAW) process. These sections can be produced as welded or, if required, be heated up to normalizing temperature.[3]

Computer

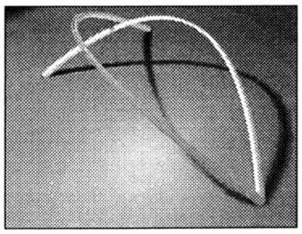
The computer is becoming more prevalent and useful in all branches of architecture, from office management to energy analysis of a building. The continued development of computer applications for the design of structure will make for significant savings, especially in structural and energy analysis programs. Factors of safety can be established within a structure, and the sizing of the member will reflect this. For elements where failure may not lead to a collapse, it will become possible and justifiable to apply lower factors of safety than those applied

9.1 Computer model of the building.

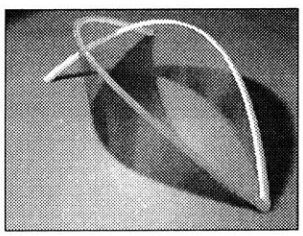




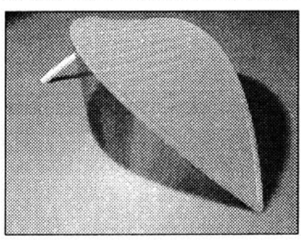
10.1 Computer model sketch of primary steel arches.



10.2 Computer model sketch of secondary structural system.



10.3 Computer model sketch of glass panel system.



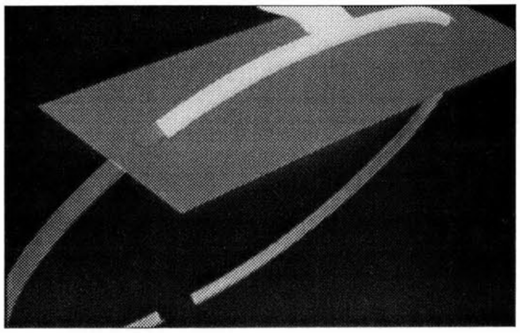
10.4 Computer model sketch of roof.

to a member whose collapse could jeopardize the stability of the total structure. [4]

The computer model of the gallery is a more accurate configuration than the physical model that was built. The curved geometries that are present in the design are accurately calculated and modeled in the computer. The computer model is helpful in that it is able to give the coordinates of the elements, especially the arches, and thereby able to assist in the structural analysis and assembly of the building.

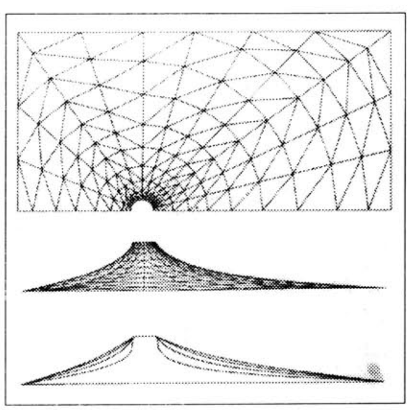
Furthermore, designers will be able to adopt a more holistic approach to design, choosing solutions which will be based on considerations of a broader nature - choosing, for instance, structural materials for the ability to meet thermal requirements: concrete for buildings requiring a stable environment, steel for buildings subject to intermittent use.[5] Computer technology aids the architect in visualizing complex architectural shapes. Frank Gehry who uses CATIA, a software that is used in the aerospace industry, states this about computer technology: "This technology provides a way for me to get closer to the craft. In the past, there were many layers between my rough sketch and the final building, and the feeling of the design could get lost before it reached the craftsman. It feels like I've been speaking a foreign language, and now, all of a sudden, the craftsman understands me. In this case, the computer is not dehumanizing it's an interpreter." [6]

There are examples of architecture whose geometry and engineering would not have possible without the computer. As in the case of the Kansai International Airport by Renzo Piano, the conception, generation, and adjustment of the overriding geometric discipline would not have been possible without the computer (Fig. 11.1). The Piano Workshop researched and developed a building technology that matched the efficiencies of nature, and in so doing also emulated its forms. The geometry used at Kansai is toroidal. The toroid is one of the most prevalent forms found in nature, such as magnetic fields, many fruits, and convection currents. The design of the airport is a perfect example of the architect's evolving ideas, and is the product of a collaborative effort and technical expertise. Piano's Workshop has a continued interest in leading-edge technology and a vision of design as research.[7]



11.1 Computer image studying the complex curve of the roof at Kansai International Airport Terminal, Renzo Piano Building Workshop.

Computers are no longer regarded only as a time- and labor-saving documentation tool but the related applications have become an integral part of the computer in the design process. The computer can realize the complex geometries found in nature and is able to model these particular forms through its own complex calculations. The computer plays a key role in achieving the coordination necessary to achieve tight integration between space, structure, skin, and services.



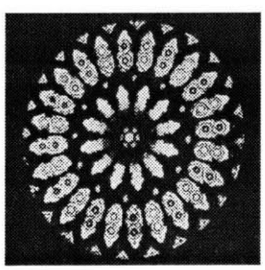
11.2 Example of Computer 'Finite Element mesh'.

Computers, based on Finite Element Analysis, were developed to mimic the modeling process. In a finite element model, the continuum is replaced by a network of discrete pieces called "finite elements". These elements are considered connected at specific points called nodes (typically at corners, but sometimes at edges). Loadings on surfaces are converted to nodal loadings. A structural model is then used to predict forces and displacements. The model used is often based on one or another of a variety of energy laws. [8] This method has now reached the stage where the limits of what can be designed and built are the limitations of materials and the limitations of the designer's inventiveness, not the limitations of analysis and specification methods. [9] This means that computers, in the process of design refinement, can produce accurate calculations that can inform the designer of the optimum and accurate conditions and specifications for materials and construction.

Glass

Through the development of new technologies, our own architecture will become more dynamic and less material, in the sense that transparent structural materials such as glass and diamond films will become the support medium for holograms, miniaturized lasers and biogenetic coatings offering the possibilities to improve energy efficiency, to create interactive building surfaces to both user and the environment, and release new creative energies in the design and visual pleasure of our buildings.

– Ian Ritchie, Royal Institutions Lecture, October 1992



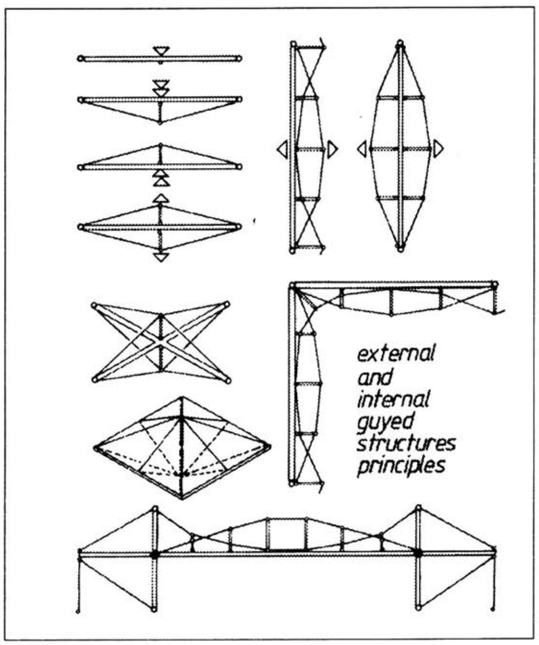
12.1 Rose window, York Minster.

In architecture, glass has been for a thousand years the medium through which light has entered buildings revealing the spatial art of architecture.[10] Colored and stained glass played a critical role in the sunlight washed windows of Gothic architecture. This is an example where the new technology of a past still expresses the spiritual.

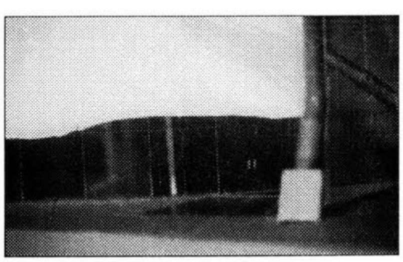
12.2 Window.

Glass is a material based on silica, seeded with metal oxides which render it transparent or opaque, black or white, or virtually any degree within these limits. Despite its apparent minimal physical presence, glass has particular physical strengths, and with some engineering, it can perform well structurally. Glass also serves as a barrier against the elements while still allowing visual contact with the outside world. The alluring qualities of transparency and reflectiveness create spontaneous images and illusions through its interplay with light. Glass is also reasonably energy efficient in terms of capital because it is recyclable and is sourced from an abundant supply making it relatively acceptable ecologically.[11]

In this art gallery, a glass panel system constitute the walls. The primary concern is that the support structure for the glass creates minimal visual disturbance. The logical solution is a guyed structure. The principle behind guyed glass structure is that "short and slender metal compression bars are used along with long thin metal tension bars and glass plates where invisible normal stresses in the form of tension or compression stresses are included."[12] Fig. 13.1 shows examples of open and closed structural schemes, of attachments to substructure, and of single-sided and double-sided schemes. The glazing system should not rest on retaining walls. Thus, the walls can pull outside the main footprint of the building which are defined by the invisible lines drawn by the hovering arches. The glazing system in the art gallery would then be pulled down by tensile members and anchored by footings below the basement. This articulates a space that can be further emphasized by light. By making that sliver between the edge of the retaining wall and the glazing wall a glass floor, a glass "moat" is created. This allows for light to enter a potentially dungeon-like space and furthermore provides a connection between the main structure and the basement. The administration offices, storage, and workshops are located in the basement, along with additional gallery space (Fig. 27). This displacement also articulates the groundscape for the site providing some reference of boundaries for the user. The "moat" occurs

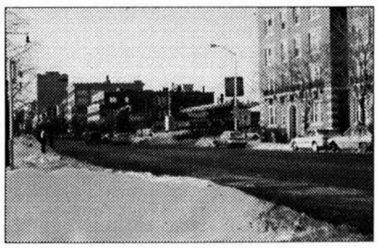


13.1 Diagrams of guyed glass structures.



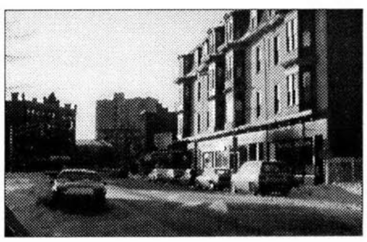
13.2 Entrance to gallery.

only on the south side of the gallery and draws the user to the main entrance of the building which is the crevice formed by the intersection of the arches (Fig. 13.2).



14.1 View down Massachusetts Avenue.

The south side of the building has much more pedestrian and vehicular traffic than the north side which appears as the "back door" of the gallery. Nonetheless the facade on the north side maintains visual contact with the public. There is a difference in height of the arches and the roof, and this gesture dictates the more prominent side of the building - the south side. The resulting slant of the roof also provides more shading from southern sun exposure.



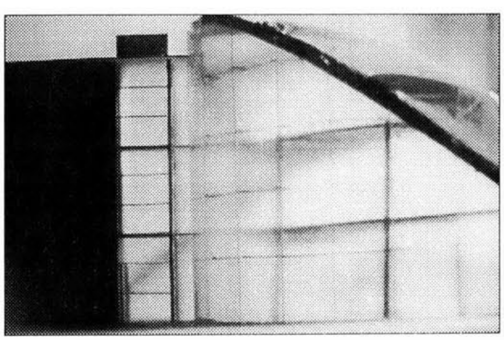
14.2 View down Main Street.

The north side faces Main Street and is located across the street from several restaurants. The mechanical building is also located on the north side of the building. The residual space between the art gallery and the rest of the buildings on the site provides a physical connection between Massachusetts Avenue and Main Street.

Light

Architecture must set forth places whose vitality of spirit can liberate man in the context of daily life. Light is what awakens architecture to life; what informs it with power.

– Tadao Ando

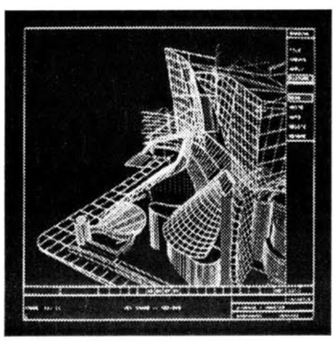


14.3 View of the gallery's north side.

Light is the "immaterial" element essential to architecture. It provides energy. It is the component that further articulates the building structure, giving it another dimension. Typically art galleries and museums are solid boxes, for specific technical and security reasons. The role that natural light plays in this art gallery in conjunction with the exterior glass walls is to emphasize the notion of the connection between the public and art. The light is a "dynamic" material wherein it changes the character of a space with the changing of time. Light alters the mood of space and with that, affects the mood of the person in that space. Without light there is no architecture. It is the ultimate connection in architecture.

The light in the main gallery indicates that that is the center of activity in the gallery. The three-story mechanical building has a diffuse quality of light. The structure of the building emphasizes this quality, denying the spaces direct sunlight, but yet allowing some light in(Fig. 25.3). Light defines the zone between the art gallery and the "mechanical" building providing a transition zone between the transparent and the opaque as illustrated by Fig. 29.1.

Details



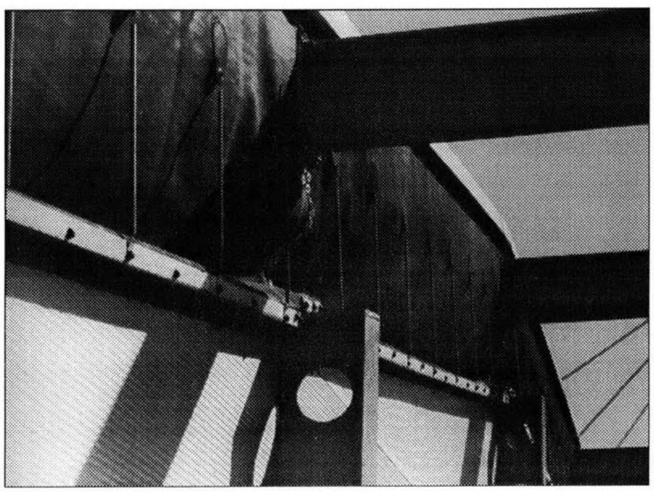
15.1 Walt Disney Concert Hall, Frank Gehry. Wireframe view modeled in CATIA.

The knowledge of how things are put together is a primary concern for architects. The design process for details is aided by the making of full size mock-ups and prototypes. These not only help make aesthetic decisions, but also test the ease of assembly, and replacement. These prototypes are used to confirm theoretical analysis.[13]

Details transform dreams and concepts into tangible reality and physical space. The resulting space is articulated by details. Details make the architecture complete. Details provide unity and coherence of parts, establishes hierarchies, gives historic reference and informs the third dimension.

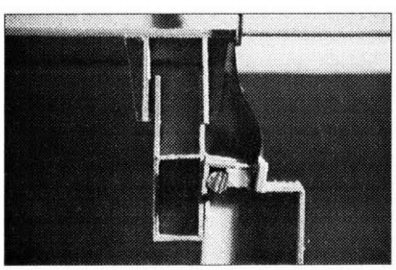
The technology that is commonly used in rapid prototyping and modeling is CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) . It has been a technology used to manufacture specialized building components or joints. CAM has been a prevalent component in the automotive, electronics, plastics, appliances and aerospace industry. CAD/CAM refers to "the integration of computers into the production process to improve productivity."[14] The designer creates a product design in detail on a computer and commands the system to make a hard copy. CAM is a process which employs computer technology to manage and control the operations of a manufacturing facility.

16.1 Eaves detail, Renault Center by Norman Foster.

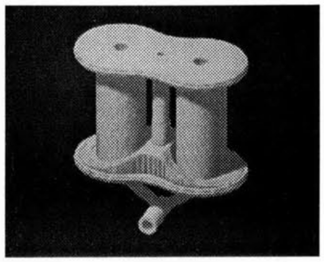


CAM exists in many forms, but the preferred method is the CNC (Computerized Numerical Control) programming which is used for "operational processing, including robotic programming and operation."[15] It is a technique by which a machine tool control uses a computer to store NC data generated earlier by a CAD/CAM system. And if the model is not first generated in CAD, then the handmade model can be digitized into the computer and modeled. Frank Gehry used this technology with the Disney Concert Hall project (Fig. 15.1). The digitizer read the key points on the physical model which was then translated into x-y-z coordinates by a nearby microcomputer which then fed the data into their modeling software CATIA. The data was manipulated to "rationalize" the complex forms into mathematically definable curves and cylinders that describe the shapes of the limestone panels. This information also helped calculate the number of "unique" panels to reduce costs.

16.2 Precedent study model.



The connection I focused on is the joint that stems off the arches to include the suspended glass panel system and the roof. I foresaw movement caused by lateral and vertical loads and thus I needed to design a joint that would adjust to these movements. The precedent model that I studied is the joint between the roof and the glazing system of the Renault Centre by Norman Fosters (Fig. 16.1, 16.2). The feature of the joint is the neoprene flap that seals off the gap between the roof structure and the structure that supports the glazing system. The neoprene allows for movement of the roof.

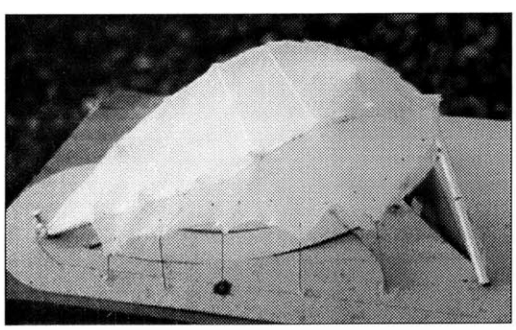


17.1 Sketch model of spring bracket.

This concept was incorporated into the design of the system connecting the main structural element with the roof and glazing joint. The collar with the component to secure the roof membrane is alternated with a collar that has the spring joint that is attached to the top glass panel. The spring adjusts to the movement of the structure. These collars are welded in place to the arches. Fig. 17.1 shows a computer sketch model of the spring bracket that could easily be fabricated by a CNC milling machine.

Roof

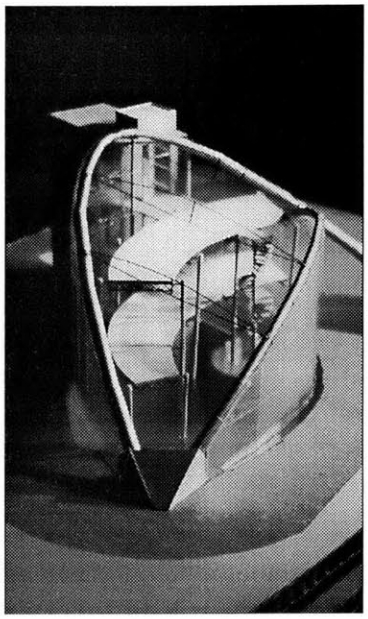
There are several alternatives to fill the interstitial space formed by the arches. One option I explored was a hyberbolic parabaloid in lightweight concrete. The other, which I chose instead, was a light fabric-wrapped steel structure that "ties" the arches together. This option allows diffuse light to enter, and the residual space formed by the steel structure to be used for some mechanical equipment.



17.2 Roof study model.

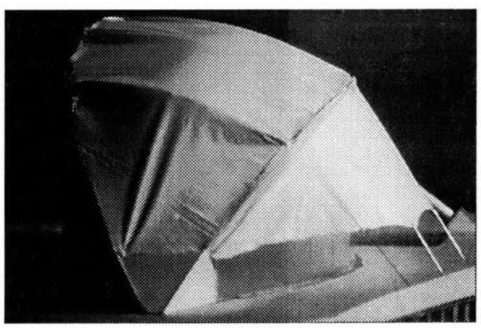
Lightweight structures, surface structures made from fabrics, tension or compression nets are lightweight because "nets or fabric are the lightest available materials with adequate structural properties to span in two directions."[16] These structures introduce a

18.1 Model of gallery without roof membrane.



whole new set of possibilities and vocabulary in architecture.

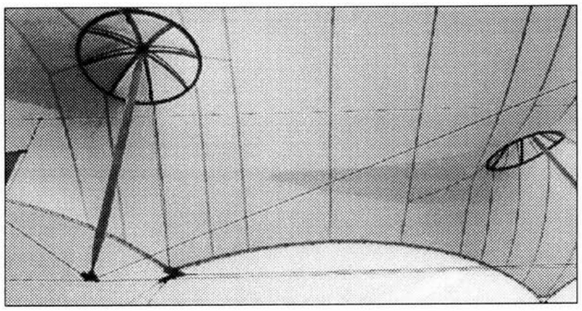
The free-form shapes that can be created by the inherent qualities of the fabric contribute to openness and "casualness" of the building. The fabric also gives the building an ephemeral or temporary quality, in an effort to stray from the typical vault-like space of an art gallery. This further emphasizes the intent to establish the connection between the public and art, and user and building. It is the optimum choice of material for this gallery. The shape must have the following characteristics in order for it to function properly. The principal characteristic it must have is an "anti-clastic curvature" at all points in the surface. "Anti-clastic" is defined by two cross-sections at right angles to each other, in which the curvature in the one direction is the opposite to the curvature in the other direction, so that the fabric is tensioned against itself. If these characteristics are not taken into account, the fabric will flap in windy conditions or under other non-regular loading and eventually destroy itself. A second characteristic is that the fabric must be pre-stressed. This means that the fabric must be tensioned up in such a way that under no-load the fabric retains tension in both directions throughout its surface and this tension is such that one direction is pulling against the other direction of tension.[17]



18.2 Model of gallery with roof in place.

There are different kinds of fabric. The most commonly used is the Teflon-coated fiberglass (polytetrafluoroethylene; PTFE), which is a relatively stiff fabric and permanent in nature. The Teflon is a non-deteriorating plastic and the glass fiber that is the load-carrying element within the fabric has the characteristics of glass so it is comparatively stiff.[18] This means that the cut of the fabric has to be precise so that there are no creases and at no point in the fabric will there be lack of pre-stress.

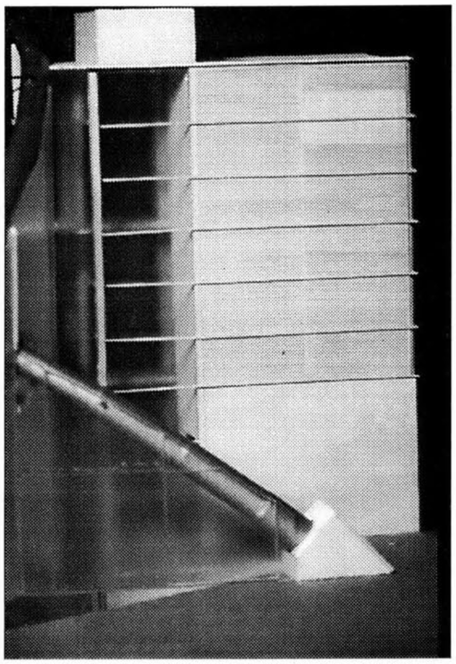
One of the alluring qualities about fabric is its translucency. The resulting seams from the cutting patterns define the shape and the assemblage of the final form. Without the seams and patterns it's difficult to see the curvature and shape of the fabric. Again the computer method based on Finite Element Analysis can be used to model these free-form shapes which would also inform the designer how the piece would be patterned. The PFTE is pure white once it has bleached to its equilibrium.[19] Light, filtered through the roof (and glazing) gives the space a more dynamic character. Throughout the day, the light creates a different space every hour, every minute. A connection is maintained between the internal and external environments. The dynamic quality of changing light will also influence the presentation of the art work perhaps uncovering new perspectives as the public will observe the pieces in different conditions within the space of a single day.



19.1 Schlumberger Headquarters.

Energy

The decision to use glass skin and a fabric roof, however, creates problems for the gallery environment. During the summer the building would virtually become a greenhouse, and in the winter the glass panels would promote condensation. The building skin should serve more than just an "environment rejecting" skin. In climates there is much high density solar radiation, the control of both air and radiant solar gains are considered to be the most important thermal design criteria.[20] These conditions call for excess building services making up for the inadequacies of the building fabric. The challenge is to stray away from add-on equipment and attempt to integrate the overall building structure itself with the mechanical system. The building then becomes a living breathing organism where components and elements are interdependent with each other in order to function.



20.1 Model of "mechanical" building.

The mechanical equipment is located in the three-story building that is plugged into the main building along Main Street. It houses the bathrooms, additional storage area, the loading dock and a mechanical room for the elevator. The building is a "dumb" box that is simply constructed. The exterior is articulated by louvers which allow indirect light to enter and maintain privacy for the services. The supply air would be pumped from the basement and through the ducts connected to the doubled glazed wall. The air between the glass would then be heated up by solar radiation and either released into the gallery space or taken through the hollow arches to get rid of the "used" air. The roof structure is basically wrapped in fabric providing thermal insulation.

Language

These components provide the vocabulary for the language that is articulated through this building. This vocabulary weaves in and out between the physical and metaphysical realms and ultimately communicates the building's idea. The components simply describe new materials and technology. The various permutations of these components produce a plethora of new vocabularies that were discussed before.

What is the connection that is being established through this language? The details of the buildings tell the story of the building. The complete story from the structural expression of the details which inform the general story of the whole building. This is an expression of the language spoken. The details embody the concept of the building. One can see the way the material is manipulated and the assemblage of the separate components through the details. In many ways, the design of buildings is analogous to that of clothing. The holes cut in cloth for the head, arms, and legs have always been opportunities for special treatment or decoration. The various approaches to cutting fabric, detailing seams, and finishing edges have helped to create styles.[21]

Many of the motifs used in architectural detail are, like logos, "highly compressed visual abstractions of ideas that would take up more space if they were fully explained."[22] Details provide that visual connection for the user. The pure structural expression embodies its own aesthetic and truth. It makes the connection with industry and technology. The details articulate to the user how the building is assembled creating the connection between the user and the building. These dynamic connections inform the overall expression of the building by establishing a more dynamic relationship with the public. The decision not to encase or conceal the structural details contributes to the expressions of the craft of the building.

Conclusion

If you want to plan a year ahead,
plant a tree
If you want to plan ten years ahead,
sow a seed
If you want to plan one hundred years ahead,
educate the people.

– Kuan Tzu (Chinese poet) 500 BC

There needs to be an understanding of the technological developments in other disciplines and how we can learn from the process of research and development that is carried out in other disciplines. We need to be connected. A good working relationship with industry is vital to the realization of excellent & innovative architectural ideas. "The architectural profession must maintain a neutral art and science platform for the exchange of views and ideas with special emphasis on encouraging and enhancing interdisciplinary technology transfer, to secure a vision of the future." [23]

Research and the accessibility of technology definitely offers more opportunities for architectural expression. Not to say that it makes design aesthetically better, but rather that now it's a matter of what is available to us to help us realize the design conception rather than what do we need to compromise according to limited specifications.

In terms of enclosing a building, making a building, and understanding how to do so, I've only just begun. There were many processes and methods that I was unable to tackle but this exploration was just the beginning of what I wish to delve into.

On a general level, Connections dealt with the obvious fact that one component could not be dealt with without the other. However; on a more specific level, exploring the concept of the interrelationship between the physical and metaphorical aspect of the building was truly inspiring. Once each component was understood, the combination produced, what I hope, a dynamic architecture.

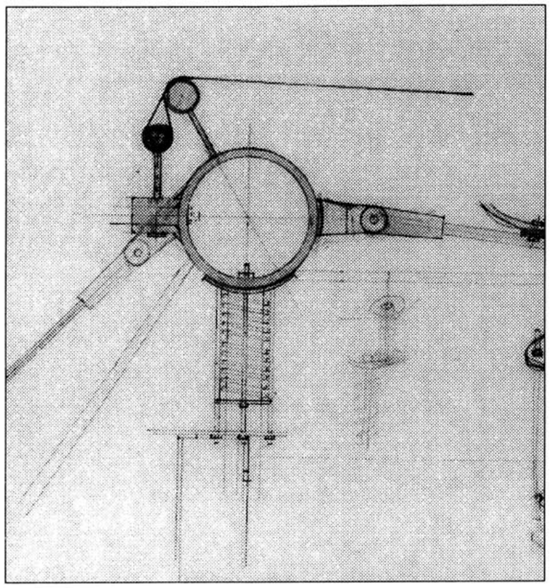
Practicing architecture at the end of the 20th century requires us to restate that it is a synthetic process. Its material foundation has for the last few centuries been knowledge established largely through reductionist science. This knowledge base is beginning to shift. Chaos theory and the science of complexity explored through computer simulation indicate how matter and life itself apparently synthesize from simple elements into simple systems with complex organizational and behavioral characteristics. This is a conceptual way of thinking that builds up rather than breaks down, recognizing interdependence rather than independence in much the same way that we seek to produce our architecture.

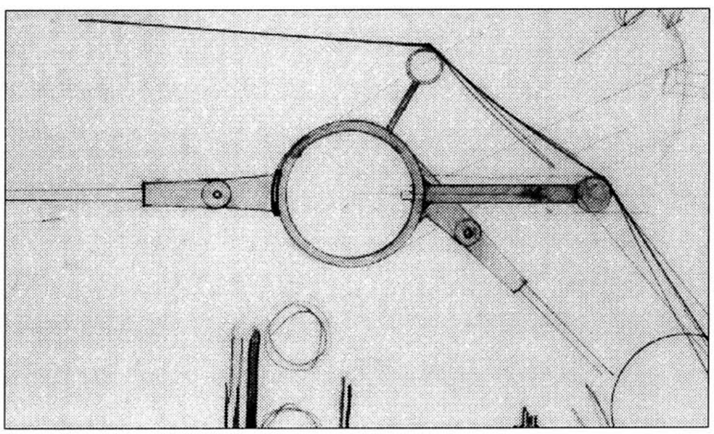
– Ian Ritchie, (Well) Connected Architecture, 1994.

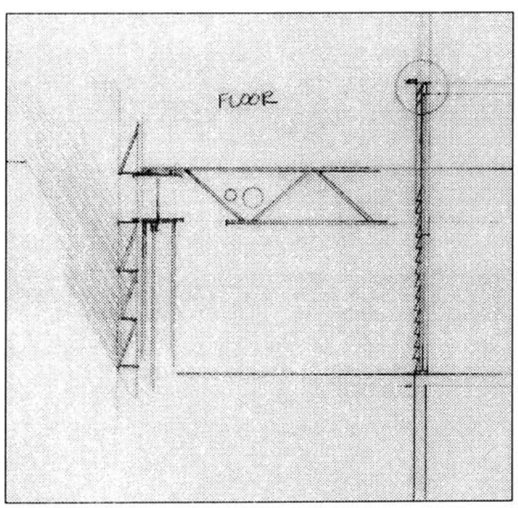
Program

This is an art gallery for up and coming regional and local artists and designers. Located in Cambridge, the gallery provides the artists an opportunity to display their work. Below are the approximate square footages of usable space in the gallery.

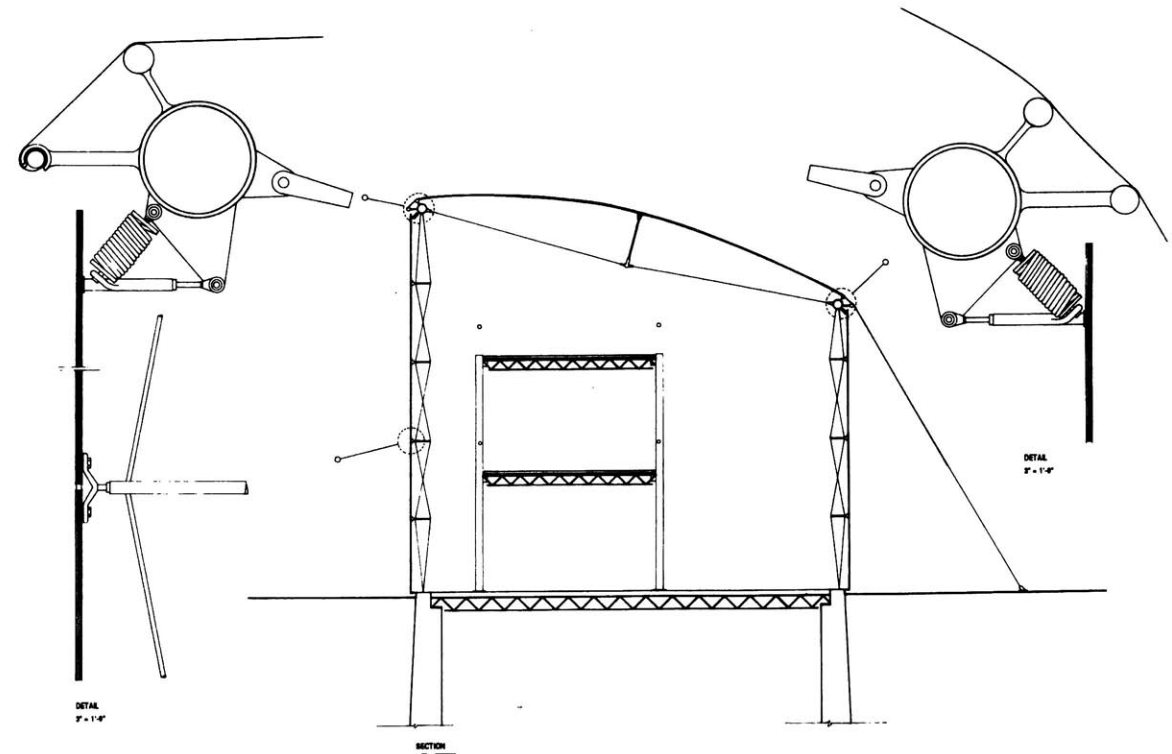
Display Area:	2400
Administration/Workshop/Storage:	1600
Additional Storage:	200
Bathrooms:	200
Loading Area:	100
Total square footage:	4500

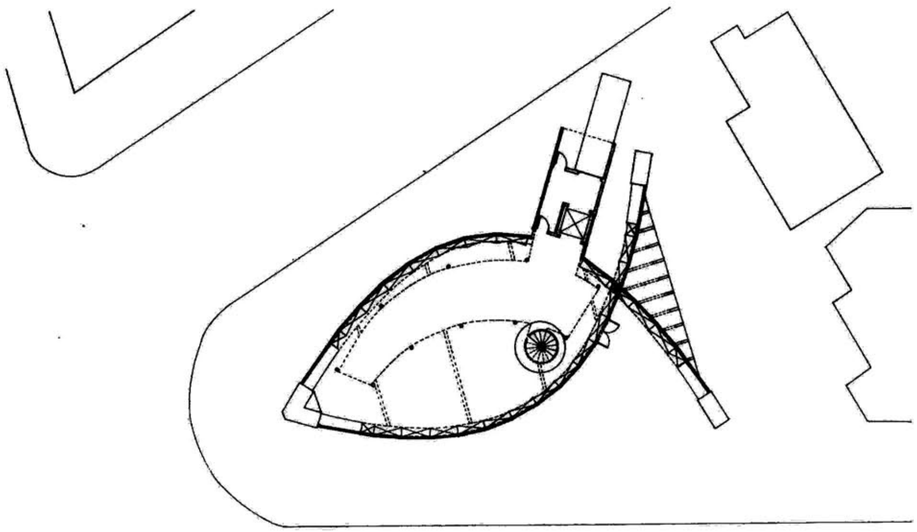




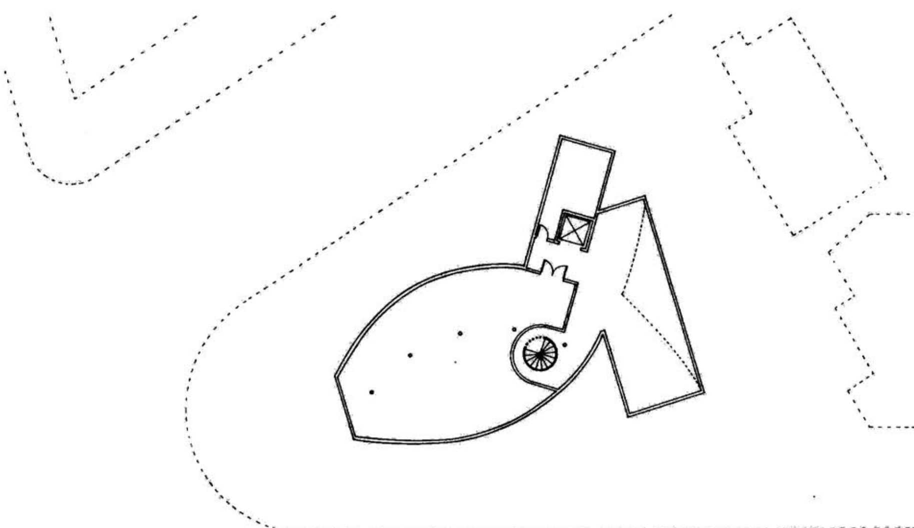


25.1 (top)
Sketch of joint.
25.2 (middle)
Sketch of joint
25.3 (bottom)
Sketch of wall section of the "mechanical" building.

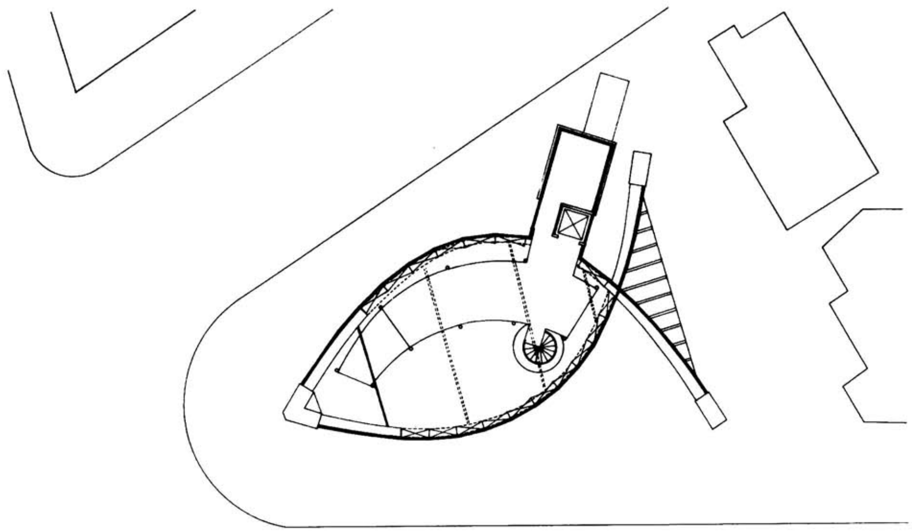

DETAIL
3" = 1'-0"
DETAIL
3" = 1'-0"
SECTION



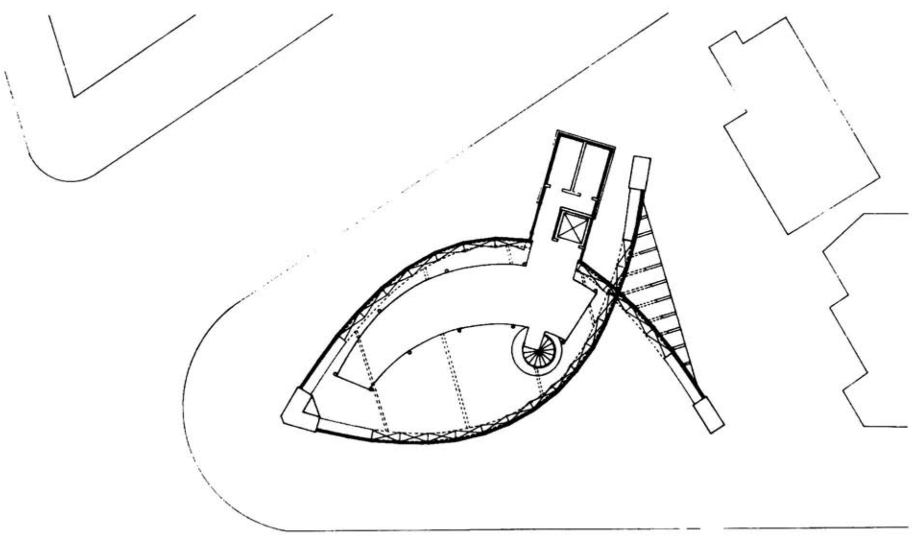
GROUND FLOOR PLAN



BASEMENT PLAN

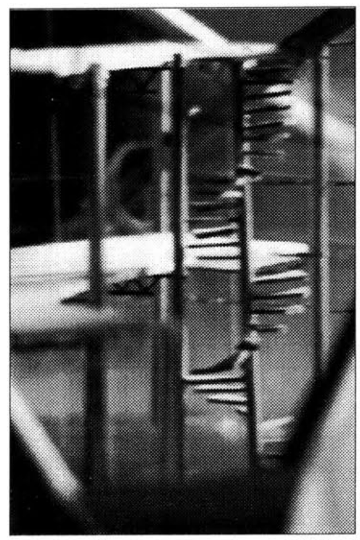


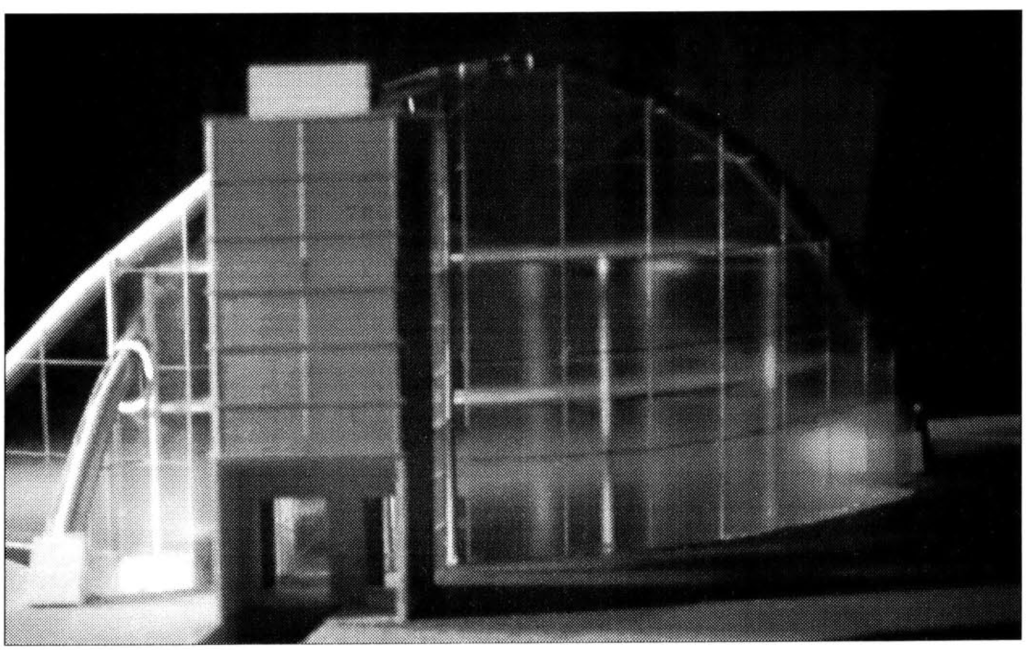
SECOND FLOOR PLAN



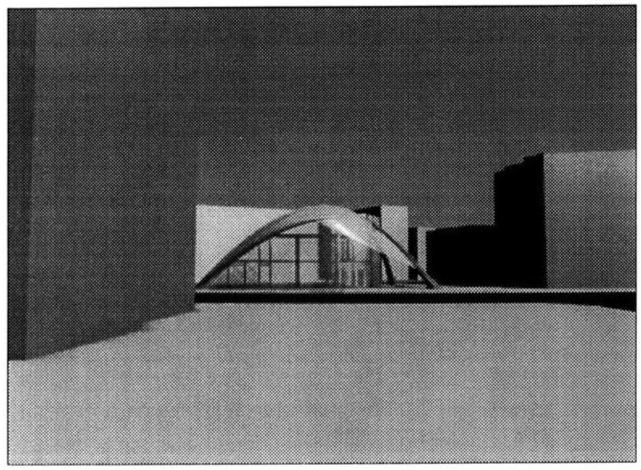
FIRST FLOOR PLAN

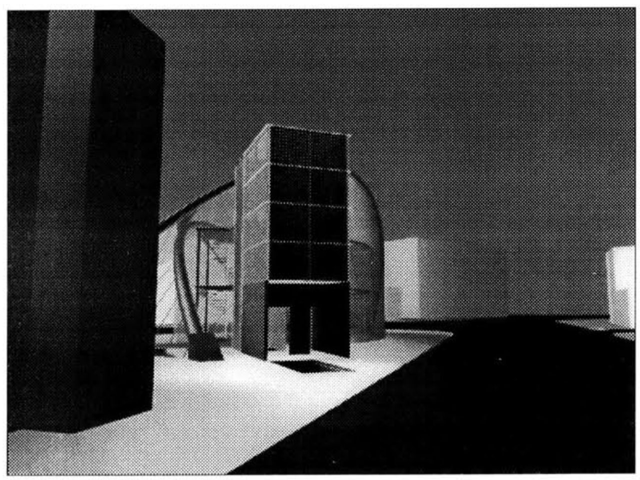
29.1 (left) View of north side and the "mechanical building.
29.2 (below right) Interior view of platforms and staircase.
29.3 (bottom) View of north elevation.

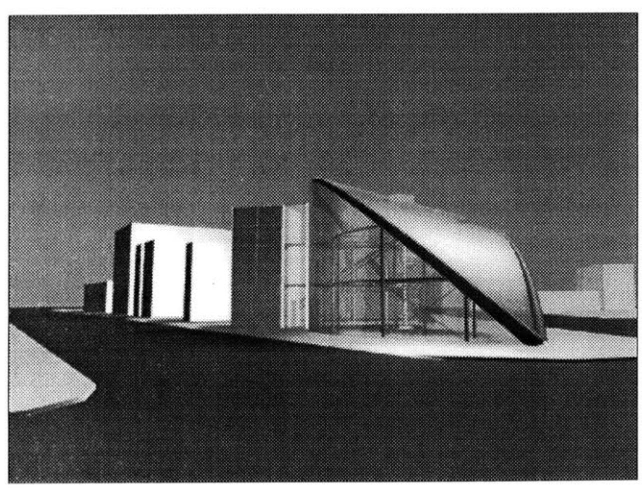




30.1 Computer model showing the view from across Massachusetts Avenue.
30.2 View from Main Street.
30.3 Front view of gallery.







30

Endnotes

[1] Blanc, p. 62.

[2] Blanc, p. 62. Structural steel can be slowly cooled in a furnace (annealed) or after somewhat faster cooling in the air (normalized). The term 'as rolled' is close to but slower than normalizing. The bars are simply left to cool where they lay.

[3] Blanc, p.62.

[4] Blanc, p. 590.

5 Blanc, p. 590.

[6] Novitski, p. 105.

[7] Buchanan, p. 6.

[8] Schodek, p. 544.

[9] Rice, p. 95.

[10] Ritchie, p. 56.

[11] Ritchie, p. 57.

[12] Eekhout, p. 21.

[13] Ritchie, p. 75.

[14] Frost, p. 14.

[15] Frost, p. 15.

[16] Rice, p.95.

[17] Rice, p. 96.

[18] Rice, p. 96.

[19] Rice, p.96.

[20] Battle and McCarthy, p.

[21] Woodbridge, p. 7.

[22] Woodbridge, p. 8.

[23] Battle, p. 28.

Credits

All illustrations and photographs by author unless otherwise noted.

3.1 Conceptual Model.
5.1 Model of the Art Gallery.
7.1 Computer-generated model of arches.
7.2 Bay of the roof of the Channel Tunnel Railway Terminal Building, Nicholas Grimshaw. Keith Collie and Mick Thomas - Structure, Space and Skin
8.1 Site Plan
8.2 View of site from Massachusetts Avenue
9.1 Computer model of the gallery.
10.1 Computer model sketch of primary steel arches.
10.2 Computer model sketch of secondary structural system.
10.3 Computer model sketch of glass panel system.
10.4 Computer model sketch of roof.
11.1 Computer image studying the complex curve of the roof at Kansai International Airport Terminal, Renzo Piano Building Workshop. Peter Buchanan - Renzo Piano Building Workshop, Vol.1
11.2 Example of Computer 'Finite Element mesh.' Ove Arup Partners - An Engineer Imagines
12.1 Rose window, York Minster. ibid
12.2 Window.
13.1 Diagrams of Guyed Glass Structures. Mick Eekhout - Product Development in Glass Structures
13.2 Entrance to Gallery
14.1 View down Massachusetts Avenue
14.2 View down Main Street
14.3 View of the Gallery's north side.
15.1 Walt Disney Concert Hall, Frank Gehry. Wireframe view modeled in CATIA. B.J. Novitski - "Gehry Forges New Computer Links" , Architecture, August, 1992

16.1 Eaves details. Dennis Gilbert - Renault Center, Norman Foster

16.2 Precedent study model.

17.1 Sketch model of spring bracket.

17.2 Roof study model. Christian T. R. Powers

18.1 Model of Gallery without roof membrane.

18.2 Model of gallery with roof in place.

19.1 Schlumberger Headquarters.

20.1 Model of "mechanical" building.

25.1 (top) Sketch of joint.

25.2 (middle) Sketch of joint

25.3 (bottom) Sketch of wall section of the "mechanical" building.

26 Section and Details.

27 Basement (bottom) and Ground Floor Plans.

28 First (bottom) and Second Floor Plans.

29.1 (left) View of north side and the "mechanical building.

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29.3 (bottom) view of north elevation.

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Bibliography

Abel, Chris, Renault Centre, Norman Foster. Architecture Design and Technology Press, London, 1991.

Battle, Guy and Christopher McCarthy, "Multi-Source Synthesis: A Future Engineering Response to Climatic Forces in Architecture". July/August 1993, Architectural Design.

Blanc, Alan, Michael McEnvoy and Roger Plank, Architecture and Construction in Steel. E & FN Spon, London, 1993.

Brookes, Alan J., Connections. Butterworth-Heinemann Ltd., Oxford, 1992.

Buchanan, Peter, "The Flight to the Twenty-First Century". November 1994, Architectural Review.

Eekhout, Mick, Product Development in Glass Structures. Uitgeverij 010 Publishers, Rotterdam, 1990.

Frost, Terry, CAM and Manufactured Housing. CMHC, Ottawa, Ontario, 1985.

Novitski, B.J., "Gehry Forges New Computer Links". August 1992, Architecture.

Pawley, Martin, Theory and Design in the Second Machine Age. Basil Blackwell, Oxford England, 1990.

Rice, Peter, An Engineer Imagines. Artemis, London, 1994.

Ritchie, Ian, (Well) Connected Architecture. Academy

Group Ltd., London, 1994.

Schodek, Daniel, Structures. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1992.

Strike, James, Construction Into Design. Butterworth-Heinemann Ltd., Oxford, 1992.

Woodbridge, Sally B., Details. The Architect's Art. Chronicle Books, San Francisco, 1991.

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